AD-A169 448 FINAL REPORT ON CONTRACT N00014-76-C-0288 1 SEPTEMBER 1975 - 15 JANUARY 1..(U) RENSSELAER POLYTECHNIC INST TROY NY DEPT OF MATHEMATICAL SCIE.. 1/1

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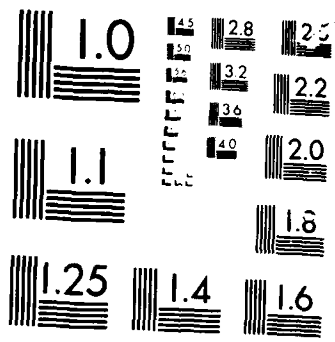

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Final Report
Contract No. N00014-76-C-0288
1 September 1975 - 15 January 1986

by

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ABSTRACT

This is the Final Report for O.N.R. Contract No. N00014-76-C-0288. It summarizes research results and lists publications, presentations, and supported graduate students.

INTRODUCTION

This final Report summarizes progress under Office of Naval Research Contract Number N00014-76-C-0288 between 1 September 1975 and 15 January 1986.

Section I abstracts our research in three general areas: (A) Environmental Acoustics, (B) Moving Sources and/or Receivers; and (C) Basic Theory. Studies under (A) are divided into four categories: (1) Eddies and Fronts, (2) Currents, (3) Bottom Effects, and (4) Internal Waves and Tides.

Thirty-four publications are listed chronologically in Section II, and thirty presentations are indicated in Section III. Section IV lists eighteen graduate students whose research was supported in part by this Contract.

I. RESEARCH SUMMARY

A. Environmental-Acoustics

(1) Eddies and Fronts

In Reference 8, an analytical approach is used to obtain an approximate solution for deep-ocean mesoscale eddies, including depth-dependent effects. The solution is used in the development of an environmental-acoustics model which relates acoustically relevant quantities, such as sound-speed and current distributions, to eddy parameters. Parameters of the model are depth of influence, radius, rotational direction and maximum speed, and translational velocity. An application to a particular Gulf Stream ring is made, and the resulting current and sound-speed structures are shown to be in qualitative agreement with observations. Then, general results are presented for rotational current structure, maximum horizontal sound-speed change, and maximum SOFAR-axis elevation as functions of eddy radius and peak current speed. It is shown explicitly how these quantities change significantly with eddy size and strength. This model provides a basis for subsequent analytical studies of sound transmission through an arbitrary eddy or eddy field.

The effects of sound-speed and current variations induced by a mesoscale cyclonic eddy on short-range propagation are considered.[15] A parametric eddy model is used to determine acoustically relevant eddy environmental effects, so that eddy-acoustical effects can be determined for eddies of arbitrary size, strength, and position. Approximations to sound-speed and current structures are used to investigate eddy effects on the three-dimensionality of rays and on ray types. The influence of current and sound-speed variations on travel time is examined, and accurate expressions for per-ray phase variation are obtained. Examples are presented illustrating effects of source-receiver position and orientation on perray phase shifts and relative phase spreading

of arrivals. Also, general results are presented which illustrate the variations of eddy-acoustical effects as functions of source-receiver range and of eddy size and strength.

Underwater sound transmissions are significantly affected by the presence of mesoscale eddies, because large sound-speed variations and rotational currents are associated with these phenomena. Using an earlier axisymmetric eddy model, equations and graphs of the ocean surface are found above an eddy.[11] The surface is elevated above an anticyclonic eddy and depressed in the cyclonic case (northern hemisphere). This behavior may be used to detect and partially classify an ocean eddy. With an appropriate eddy model, satellite altimeter data may be used to approximate acoustically-relevant effects.

The use of analytical modeling in the study of oceanic eddies is considered.[12] Limited observational data, in combination with eddy models, are used to obtain analytical approximations to environmental effects (including current and temperature perturbations) throughout the eddy. Techniques which efficiently use discrete measurements are presented for accurate specification of any given analytical model, containing an arbitrary number of parameters, to an observed eddy. Questions of unique parameter specification and data sufficiency are considered for various data types and amounts, using a previosuly derived eddy model. Examples with bathythermograph data are presented in which eddy size, strength and center position are to be determined. AXBT data are emphasized, and an investigation is made of the influence of the number of such instruments on the accuracy of parameter estimates. It is then shown how data obtained from oceanographic moorings might be utilized to specify eddy drift speed and direction. In both the bathythermograph and mooring examples, it is demonstrated that even when the type of data available leads to non-unique parameter specification, significant information can be

obtained about the observed eddy. Results in this paper suggest possible efficiencies in data utilization and in the design of subsequent experiments.

An analysis of a perturbed idealized cyclonic mesoscale eddy is performed.[21] Included are random perturbations from perfectly circular streamlines and random perturbations in current magnitude. The random current fluctuations are required to satisfy conservation of mass. Short-range acoustic transmission through the perturbed eddy are considered, and an approximate solution of the ray equations is found. An approximation for ray travel times is developed in terms of the horizontally averaged, source-receiver current component, and travel-time statistics are investigated. Travel times over different ray paths are nearly perfectly correlated, implying that current perturbations can have significant effects on total-field phase, but have little effect on total-field intensity. Statistics of the horizontally averaged current components are analyzed and their effects on travel times and acoustic phase are determined for various source and receiver locations in the eddy. Source-receiver orientation is shown to be crucial in determining current effect on both the mean and the standard deviation of phase.

In Reference 23, consequences of eddy-induced sound-speed and current variations on acoustic propagation between a submerged source and receiver are considered using ray theory. For ranges of tens of km, those rays which exist for particular source and receiver depth and range values are determined and studied. Sound-speed and current effects on per-ray travel time and spreading loss are investigated. Changes in the former of 15 ms or more are demonstrated, depending on source and receiver locations and ray type. Then, eddy effects on total-field amplitude and phase are examined. For a cw sound signal of 400 Hz, variations of about 25 dB in amplitude and several cycles of

phase are observed as source and receiver positions vary within a typical eddy. Eddy currents alone are shown to have a relatively significant effect away from the eddy center, when certain rays are present or absent, and when source and receiver change their orientations. Indeed, current effects by themselves can lead to variations of up to about 12 dB in amplitude and 0.9 cycles in phase.

An approximate ray-acoustic model is used to obtain general information and overall results for long-range sound propagation through mesoscale cyclonic and anticyclonic eddies of arbitrary size and strength.[26] Two-dimensional ray approximations are employed, and currents and horizontal sound-speed variations are averaged along approximate paths within an eddy. Eddy-induced per-ray travel-time changes are shown to depend nearly linearly on current strength and piecewise linearly on eddy size. For transmission ranges of about 1000 km, the presence of the eddy may cause per-ray travel time to increase (or decrease) by nearly 200 ms in the cyclonic (or anticyclonic) case. Variations in eddy current strength alone are shown to cause changes of about 100 ms in per-ray travel time. Currents may cause travel-time changes which are as much as those due to sound-speed variations close to eddy edge, and which are as much as 15% of sound-speed effects elsewhere. This suggests that in an acoustic tomography procedure, a corresponding percentage error in predicted sound-speed variations may arise by neglecting currents. In some total-field examples, it is shown that variations in eddy size and strength, and in source and receiver location, can cause an increase of about 5 dB or decrease of over 10 dB in transmission loss, relative to the case when the eddy is absent. Further, it is shown that explicit inclusion of currents alone may cause an icrease or decrease of over 10 dB in transmission loss.

The effects of sound-speed variations produced by shallow (less than 300 m)

deep-ocean fronts on short-range acoustic transmission between surfaced sound source and receiver are investigated[24] using ray theory. A parametric model of such fronts, based on observational data, is constructed via sound-speed profiles which are trilinear with depth. The model is sufficiently general to permit determination of acoustical effects for fronts of varying strengths, vertical extents, and positions within the propagation range. Frontal influences on travel time and geometrical spreading loss are examined, and expressions for per-ray amplitude and phase are developed for cw transmissions with source and receiver near the surface. Then, the dependence of total-field, amplitude and phase on frontal strength, vertical extent, and relative location are determined. All these frontal quantities are demonstrated to produce significant acoustical variations, such as total-field transmission-loss changes of more than 6 dB depending on frontal location. Simple and accurate approximations to both per-ray and total-field variations are presented which could predict changes in these quantities due to shallow fronts.

In Reference 34, the effects of a front on short-range acoustic transmission between source and receiver at arbitrary depths in shallow water are investigated using ray theory. A simple parametric frontal model, based on observed data, is employed for the sound-speed and current distributions associated with the front. This model facilitates the analysis of the acoustical consequences of frontal strengths and relative positions within the propagation range. Frontal influence on per-ray quantities, including travel time and spreading loss, are examined for cw transmission. Certain significant variations are shown to occur, such as travel time changes of more than 30 ms over a range of 20 km depending on front location. The dependence of the total acoustic field on frontal sound-speed and current strengths, orientation, and relative location is also determined. Total-field transmission-loss changes of

more than 9 dB are produced for different relative frontal locations. A procedure is indicated for using acoustic receptions from multiple sources and receivers to estimate the physical and geometric properties of a front. Frontal influence on the beam pattern of a uniformly-spaced, horizontal linear array is found to alter main beam direction and relative received amplitude.

(2) Currents

The effect of currents on the acoustic pressure field in an underwater sound channel is investigated.[31] Based on fundamental fluid equations, model equations are formulated for sound pressure while the including nonuniform currents in the source-receiver plane. Application of parabolic-type approximations yields a collection of parabolic equations. Each of these is valid in a different domain determined by the magnitudes of current speed, current shear, and depth variation of sound speed. Under certain conditions, it is possible to interpret current effects in terms of an effective sound speed. Using this effective sound speed in an existing numerical code, we examine sound speed in a shallow water isospeed channel with a simple shear flow and a lossy bottom. It is found that even small currents can induce very substantial variations in relative intensity. The degree of variation depends upon current speed, source and receiver geometry, and acoustic frequency. Particular emphasis is placed on intensity-difference predictions in reciprocal sound transmissions in the presence of an ocean current.

The effects of a random current on the fluctuations of underwater cw sound transmissions are considered[9] for a horizontal isospeed channel. A statistical ensemble of currents is employed, whose members are depth dependent only, and current influence on ray geometry is investigated. Approximations to the total acoustic field at a receiving point are obtained, and it is shown tha a current ensemble member has a significant effect on phase. A mean current is taken, on

which are superimposed small depth-dependent current changes in speed and direction. These changes are members of statistical ensembles, which lead to an ensemble of phase functions. Expressions for the mean and standard deviation of the phase, in terms of statistics of the depth-averaged current fluctuations, are determined and analyzed. The inverse problem of determining second-order moments of the random current, given the standard deviation of phase, is examined also. If the mean current is known, phase information at three receivers is sufficient to specify the second moments of the current fluctuations.

The effects of random fluctuations in an ocean current on underwater cw sound transmission between a bottomed source and receiver are determined[18] for an ocean channel with a linear, depth-dependent sound speed. A horizontal, depth-dependent current is considered whose components are random processes. Effects of such a current on ray geometry are determined and six basic current-induced ray states are found. Under certain conditions, including the assumption that the sound-speed gradient is larger than current-component gradients, only one ray state may arise. The geometry of this state is expressed explicitly in terms of the current. Approximations for travel times, total-field intensity, and their first and second moments are obtained. These moments depend significantly on properties of the source-receiver current component. Intensity moments are predicted using ocean-current data. For selected parameter values, a difference between relative mean intensity and relative intensity without current of as much as 9 dB and a standard deviation of relative intensity as large as 3 dB are found. These moments are rapidly varying with transmission range; however, useful bounds are derived which are slowly varying and which display an unusual behavior near certain critical ranges.

In Reference 2, results of a previous hydrodynamical study of a uniform, deep-ocean flow are used to develop simple approximations to the sound-speed and current distributions in the flow. The behavior of sound speed with depth, surface current, and source and receiver locations is examined. The effects of the flow on ray geometry, travel time, and spreading loss are investigated for a surfaced cw sound source and bottomed receiver. Total-field amplitude and phase are determined and are found to be highly sensitive to surface-current variations and to source and receiver locations. A simple method is presented for accurately estimating amplitude and phase. Then, an approximate phase formula is developed that is proportional to surface current, linear in source location, and sinusoidal in the orientation angle of the source-receiver range.

The effects of a combination of sound-speed and current fluctuations on propagation of a cw signal in a deep-ocean model are analyzed.[7] The mean sound-speed and current fluctuations on propagation of a cw signal in a deep-ocean model are analyzed. The mean sound-speed structure is assumed bilinear, and the channel boundaries are horizontal. The horizontally independent sound speed oscillates with a 12-h period, while the spatially uniform currents consist of quasisteady and diurnally varying components. The total acoustic field for surface-reflected-bottom-reflected rays is investigated for dependence on time, source-receiver separation, and environmental parameters. Multipath propagation is demonstrated for larger propagation ranges, for which case the number, depths, and occurrence times of amplitude fades are shown to be very sensitive to parameter changes. Where the total field is dominated by one ray, contributions from combined sound-speed and current fluctuations to phase are investigated. In both cases, phase generally can be influenced by both sound-speed and current fluctuations, but the former more effectively influence amplitude.

(3) Bottom Effects

Effects of random bottom structure on acoustic intensity in isospeed shallow water are studied.[29] The randomness is due to stochastic variations in the bottom density and sound speed in the horizontal direction beneath a plane water-bottom interface. Ray geometry, spreading loss, and bottom loss and phase shift are examined in order to derive formulas for mean intensity and the variance of intensity. The expressions obtained are sufficiently general to permit their use with different bottom-acoustic models of sound reflection. In this paper, for illustrative and comparative purposes, two such models, one developed by Mackenzie and the other by Raleigh, are considered. The distinctive acoustic consequences of bottoms of different density mean, variance, and horizontal correlation are discussed, as are comparisons of results for the two bottom-reflection models. Intensity moments are obtained also for differing source-receiver range and water depth.

The influence of sound-speed fluctuations on propagation of a cw signal in an ocean with a uniformly sloping bottom and a horizontal surface is analyzed[13] using ray theory. The mean sound-speed structure is modeled as bilinear, with bottomed source and receiver above and below the SOFAR axis, respectively. The horizontally independent fluctuations oscillate with a 12-h period in the upper ocean. An examination is made of possible types of rays for down-slope propagation that might exist, depending on bottom-slope angle and source-receiver separation. The total acoustic field is investigated for its dependence on these parameters and time. For certain conditions when up to three rays comprise the mean total field, three partterns of time evolution are described, each of which may have significant amplitude variations. Numerically computed examples of each type are presented. The linear relationships between phase variations of individual rays and the sound-speed fluctuations are derived.

Then, formulas are developed to explain the most frequent behavior of the relative amplitude and phase of the multipath total field. Predictions from the formulas show very good agreement with the numerical calculations.

In Reference 27, surface-reflected/bottom-reflected transmissions over a slowly sloping bottom in a deep ocean are investigated using ray theory. For convenience, sound speed is taken to be bilinear with depth in the water, while the bottom structure is assumed to be uniform. The sound source and receiver are located on or near the ocean boundaries, and the effects of bottom slope on ray geometry, per-ray travel time, and incoherent total-field amplitude are examined. For transmission ranges of tens of km, and for typical deep-ocean slope inclinations, travel time may change by about 1.0s, relative to its value for a horizontal bottom. The time difference between ray arrivals decreases (increases) in the divergent (convergent) channel. Principal effects of bottom slope on total-field amplitude arise primarily through bottom-loss modifications, rather than through spreading loss. An inclination-angle magnitude of only 0.25° is shown to cause a decrease of about 8 dB (increase of about 4 dB) in the incoherent amplitude in the convergent (divergent) channel, for ranges of about 100 km. Changing bottomed receiver location in a convergent channel, in order to improve source detectability, is shown in an example to be much more effective than in the case of a horizontal bottom. In a corresponding divergent channel, however, the strength of the acoustic reception is much less sensitive to variations in receiver location.

The effects of a sloping bottom on acoustic transmissions, between a source and receiver at arbitrary but fixed locations are investigated[33] using ray theory. An isospeed channel is assumed, and bottom angles up to about 3° are considered. Sloping bottom influence on per-ray quantities, including travel time and transmission loss, are examined for cw transmissions. Significant variations

are shown to occur, such as travel time changes of more than 200 ms over ranges of about 6 km. Per-ray transmission loss is found to be influenced strongly by bottom slope, the amount of influence depending upon source-receiver bearing and the bottom loss model used. Variations of more than 20 dB are demonstrated. Effects of a sloping bottom on the total acoustic field are examined also, and the results compared with those for a horizontal bottom. Finally, a simple model of a shallow water front is superposed over the sloping bottom, and travel time is investigated. The sloping bottom effect can induce travel-time changes more than 300% larger than the frontal effect for different source-receiver geometries and bottom inclinations.

(4) Internal Waves and Tides

A consistent hydrodynamic model is developed[5] for the effects of a stochastic field of internal waves in the deep ocean on sound-speed and current fluctuations. A scaling is used which reflects the preponderance of energy contained in internal waves of long horizontal wavelengths and near-inertial periods. An approximate solution to the consistent boundary-value problem for vertical eigenfunctions is obtained by a WKB(J) expansion. Expressions are found for internal-wave fluctuations as superpositions of deterministic functions multiplied by random variables, for which particular probability distributions are not assumed. Using specific forms of Brunt-Vaisals frequency and internal-wave energy-density spectrum for illustration, formulas for covariances, variances, confidence intervals, correlation coefficients, and correlation scales are obtained for acoustically pertinent fluctuations. As a result of the consistent treatment of vertical variations throughout the model, many properties of the statistical quantities, such as vertical nonstationarity of the variances, upper and lower correlation depths, and horizontal correlation length, are demonstrated and physically interpreted.

A consistent environmental-acoustic model for a deep moving ocean is formulated.[16] The acoustic model for regularly perturbed SOFAR rays is approximately solved using a type of WKB(J) expansion. Interfacing conditions between the hydrodynamics and acoustics are developed which lead to constraints on acoustic frequency and transmission range. As an application, transmissions are considered through stochastic internal-wave fields, which have been modeled in a previously published paper by the authors. Formulas for ray phase variances are derived. These formulas are asymptotically evaluated for rays with relatively significant depth variation, using the stationary phase method. New results are obtained for the dependence of the variances on internal-wave primitives, such as energy spectra. Expected multipath intensity is calculated for transmission through an ocean with static state modeled by a bilinear sound-speed profile. The effects of the internal-wave field and of varying internal-wave parameters on the expected intensity are shown to be significant.

A major purpose of this paper[1] is to investigate the influence of mean sound-speed structures on sound transmission in the presence of a single-frequency internal wave. A cw signal is transmitted through a shallow ocean over a range that is small compared to the wavelength of the internal wave. A constant value of the Brunt-Vaisala frequency is assumed, and this value is taken as a parameter of the model. The total field associated with refracted/bottom-reflected rays is studied, and the effect of the internal wave on total-field phase and transmission loss is examined. Then, the maximum variation of of the phase is investigated for different mean sound-speed structures and internal-wave amplitudes. This variation shows a general downward trend, as bottom sound speed increases, and an oscillatory behavior possibly due to rapid changes in the rate of change of phase with respect to mid-depth sound speed. A simple mathematical model is constructed to explain the dominant decreasing

trend. Phase variation is shown to vary linearly with bottom sound speed and to be proportional to wave amplitude, range, and acoustic frequency. It is inversely proportional to ocean depth.

B. Moving Sources and/or Receivers

A treatment of the effects of arbitrary motion of a cw source and depth-dependent sound speed on the total acoustic field at a fixed receiving point is considered for an ocean with horizontal boundaries.[4] Application of our general method is made to a constant sound-speed channel in which the range-to-depth ratio is large, when the source follows a short straight-line path with constant velocity. Total-field phase is investigated as a function of receiver time for various source trajectories and phase rate is examined in terms of an arbitrary, but fixed, acoustic frequency. It is shown that source motion may be accounted for by assuming the sound source to be stationary, and by replacing its frequency by approximate Doppler frequency. For long source trajectories, cumulative phase can be approximated as a hyperbolic function of time. The outputs of two uniform colinear arrays, together with power spectra there, are employed to illustrate one method for determining source speed, location, bearing, and frequency.

In Reference 6, analytical methods are employed to obtain general results for the effect of cw source motion on the total acoustic field at a fixed receiver in the deep ocean. A bilinear sound-speed profile is used, a long range is assumed, and SOFAR rays are considered. Equations are developed which give amplitude and phase as functions of receiver time. Then, an investigation is made of stability regions, defined as range intervals for which all rays for given numbers of SOFAR-axis crossings arrive at the receiver. Three types of such regions are identified and examined. Amplitude and phase are linearized for a short source run, and novel numerical results for these quantities are

presented. Approximate formulas for cumulative phase and Doppler-shift frequency are derived and discussed. Finally, an analytical description is presented for two mechanisms responsible for amplitude fades.

Deep-water sound transmission from a moving source to a fixed receiver is studied, where the source emits a random broadband signal whose expected distribution is normal.[10] A bilinear sound-speed profile is employed, the source is located above the SOFAR axis, and the receiver below. Long ranges are assumed, so that only SOFAR rays need be considered. Basic propagation equations are given, and travel time and spreading loss expressions are approximated in stability regions within which all four SOFAR rays exist for each number of SOFAR-axis crossings. General equations are derived for the received average power spectrum and power in terms of the spectrum at the source. Then, the broadband signal is taken to be bandlimited white noise. The received spectrum is simplified and examined for nonmultipath, multipath, and Doppler contributions. The influences of range, source speed, frequency, and observation time are considered. Average power at the receiver is studied similarly. Received spectra for a stationary source are investigated, and exhibit greater variations than those arising from a moving source. However, received average power for stationary and moving broadband sources are about equal. Average received power from cw and broadband sources, both moving and stationary, are compared. Power variations in the cw case are found to be much larger than in the broadband case.

An analytical approach is used to determine general results on a cw signal transmitted through a deep ocean channel at short ranges.[14] A bilinear sound-speed profile is used. The receiver and source are restricted to the surface, and only SRBR rays are relevant. Time-dependent expressions for the total-field amplitude and phase are developed for appropriately limited time intervals, and numerical results are presented. General analytical expressions for the total

field are derived and demonstrated to approximate closely numerical results. These expressions provide the basis for a study of the acoustical effects of varying motion parameters and initial range. It is demonstrated that effects of differences in range on total-field phase rate and the time interval between amplitude maxima are significant at short ranges and diminish as range increases. Effects on total field due to receiver motion are shown to be both significant and widely varying, depending on receiver and source directions and speeds.

In Reference 19, the effects of receiver and source motion are examined for a cw signal transmitted through a deep ocean at ranges of tens to hundreds of km. Ray theory is used to develop results for multipath signals consisting of a wide variety of combinations of SRBR and RSR ray arrivals. A bilinear sound-speed profile is assumed for which bottom and surface sound speeds need not be equal, and receiver and source are chosen to move on the surface. Numerical results are presented using time-dependent total-field expressions, valid for suitably limited time intervals. Analytical expressions are developed which closely approximate numerical results and which provide general conclusions regarding acoustical effects of receiver-source motion at different ranges. When only SRBR rays can occur, total fields are shown to have significantly different characteristics depending on range, in contrast to the virtually range-independent total fields which contain RSR rays. When total-field phase is interpreted in terms of an approximate Doppler shift, the frequency change shows relatively wide variations with both range and total-field composition. Thus, a given frequency shift at the receiver may be the result of considerably different receiver-source directions and sepeeds.

Using ray theory the combined effects of time-dependent changes in source depth and receiver-source range are examined for a cw signal transmitted over relatively short ranges.[20] Approximating deep-ocean sound speed with a bilinear

profile, general results are obtained when the receiver is taken fixed on the surface, while the source moves on an arbitrary constant-velocity path above the SOFAR axis. Time-dependent expressions for the amplitude and phase of the received multipath signal are used to present numerical data for suitably restricted time intervals. Then, the effects of source path and speed are analyzed using convenient formulas which closely approximate numerical results. For strictly horizontal motion, total-field phase rate remains approximately proportional to time, source frequency, speed, and horizontal receiver-source range, but virtually independent of source depth. However, when source depth varies with time, overall linear phase patterns are interrupted by regularly spaced, brief changes in phase rate. The periodicity of these changes, and accompanying amplitude fades of up to dB, are virtually proportional to vertical speed, source frequency, and range, but invariant with changes in horizontal speed, direction, and initial source depth.

The sensitivity of a passive horizontal-tracking algorithm to variations in input measurements is investigated.[32] The algorithm determines estimates for depth, range, bearing, horizontal speed, course, and frequency for a cw acoustic source moving with constant velocity at fixed depth. The receiver is a horiztontal linear array towed at a constant depth. Both source and receiver move in the upper portion of a deep ocean and are separated by a relatively short range. Dominant acoustic signals are presumed to arrive along two upper-ocean ray paths. The algorithm uses a new combination of input quantities, including multipath information, Doppler frequency shifts, and array directional measurements. Procedures are developed for analyzing effects of input-measurement errors on source localization. The robustness of the algorithm to small variations in acoustic measurements and environmental parameters is demonstrated for a variety of source-receiver configurations. Variance estimates of position and motion are obtained in terms of input-measurement variances. Bounds on tracker performance

are developed for measurements that are affected by noise. Results from the several types of analyses corroborate the sensitivity characteristics of the algorithm.

C. Basic Theory

A hydrodynamic model for flows in the deep ocean is developed in[3] order to determine the velocity field and sound-speed distribution for use in acoustic transmission problems. A scaling of the governing equations is constructed that explicitly includes sound speed. A subsequent perturbation expansion yields a set of approximate equations for motions nearly in geostrophic and hydrostatic balance, such as large-scale, quasisteady currents and Rossby waves. The quasigeostrophic potential vorticity equation or a simpler limiting case of this equation arises from the perturbation scheme to govern higher-order dynamics of the stream function for these flows. The results of the analysis are used to obtain a significant simplification of the ray equations of geometrical acoustics for moving media. For the particular class of flows considered here, the model equations are applicable if the ocean depth is about 1 km or greater and if the spatial and temporal scales of variation of the motions are of the order of 100 km and 10 days, respectively. A solution for a flow such as the Antilles current is derived. Isospeed curves for this solution are shown in a plane perpendicular to the current, and specific features of the curves are discussed and interpreted.

A simplified approach is described[17] for determination of phase perturbations produced by variations in sound speed and current in the ocean. It is shown that corresponding perturbations of the ray geometry may be ignored in determining the phase perturbations, when the former are regular in a specific sense. Principal advantages in the procedure include its efficiency in calculation of phase variations and its indication of situations when ray-geometric perturbations may significantly influence phase. The method is demonstrated for both shallow- and

deep-ocean examples, when the phase perturbation arises from weak horizontal deviations from a horizontally uniform sound-speed structure. It is also illustrated for current in the deep ocean, considering cases with and without horizontal variations in current speed. Examples for both types of horizontal variations are shown in which they make significant contributions to ray phase. Finally, the procedure is applied to some single-path acoustic observations in which the time series of travel time is dominated by tidal variations. Ranges of possible environmental changes in sound speed and current, leading to the observed travel-time variations, are indicated.

Geometrical spreading of sound is investigated[22] for propagation along purely refracted rays in motionless media with smooth, depth-dependent, sound-speed profiles. Fundamental characteristics of rays and spreading are derived which are valid for very general types of sound-speed distributions of importance in ocean acoustics. Ray turning and caustic-contact points are shown to either interlace or coincide. For periodic rays, the separations between adjacent turning or caustic-contact points are shown to either remain constant or approach zero with range, depending on a basic property of the ray period. Bounds are obtained for the separation distance, along with an asymptotic formula for the distance between nearest-neighbor turning and contact points. These results are extensions and a correction to those in a recent paper [W.A. Kinney and A.D. Pierce, J. Acoust. Soc. Am. 67, 1145-1148 (1980)]. Quantitative predictions from our formulas are compared with other calculations and serve to illustrate their usefulness. Several advantages of applying our formulation and results in the numerical computation of geometrical spreading are discussed.

In References 25 and 28, the sensitivity of oceanic sound transmissions to the choice of a sound-speed profile is analyzed using ray theory. The profile may be any one from a collection of depth-dependent, single-minimum profiles which can

be used to model a deep-ocean sound channel. Several configurations are considered with fixed source and receiver, separated by less than about 50 km, so that different types of ray propagation can occur. Given a specified profile, procedures are prescribed for constructing a simpler profile, for which all important acoustic quantities are either identical or negligibly different. The construction methods have physical interpretations and identify the critical aspects of profiles are shown to be very close. Useful formulas are presented which demonstrate that per-ray phases and amplitudes corresponding to the simpler profile approximate accurately those of the specified profile. The total-field phase and amplitude differences associated with the two profiles are discussed briefly. Thus, when our procedure is applied, propagation results are not sensitive to the type of profile selected.

The sensitivity of total-field receptions to sound-speed profile choice is analyzed using a ray theory. The profiles are depth dependent, and may be used to describe a deep-ocean sound channel. A variety of locations of a fixed source and receiver, separated by less than about 50 km, is considered. Given a specified profile and a second, simpler profile constructed by procedures previously described [J. Acoust. Soc. Am. 75, 112-124 (1984)], it is demonstrated that the acoustic fields associated with the profiles are negligibly different. Approximations for total-field phase and amplitude differences are presented, which facilitate the determination of those ranges where the total fields match closely. In addition, the sensitivity of performance measures for horizontal linear receiving arrays to profile selection is studied. Expressions for normalized power pattern are developed which incorporate certain nonplane-wave effects associated with an assumed dominant ray arrival. Conditions are presented for which a simpler profile may replace a specified profile and still maintain nearly equivalent array performance.

II. PUBLICATIONS

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5. "Acoustically Relevant Statistics for Stochastic Internal-Wave Models," J. Acoust. Soc. Amer., 61, 716-726, 1977.

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7. "Combined Influence of Spatially Uniform Currents and Tidally Varying Sound Speed on Acoustic Propagation in the Deep Ocean," J. Acoust. Soc. Amer., 62, 53-62, 1977.

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9. "Effect of a Random Ocean Current on Acoustic Transmission in an Isospeed Channel," J. Acoust. Soc. Amer., 62, 1165-1175, 1977.

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2. "Environmental-Acoustics Analysis of Sound-Speed Fluctuations Induced by Internal Waves," 91st Meeting of the Acoustical Society of America, 1976.

3. "Sound Speed Fluctuations Produced by a Stochastic Field of Internal Waves," Fall Meeting of the Society of Industrial and Applied Mathematics, 1976.

4. "Effect of a Random Ocean Current on Acoustic Propagation," 93rd Meeting of the Acoustical Society of America, 1977.

5. "General Analysis of Ocean Eddy Effects for Sound Transmission Applications," 93rd Meeting of the Acoustical Society of America, 1977.

6. "Use of Eddy Modeling in Studying Acoustically-Relevant Effects and Underwater-Sound Transmissions," 95th Meeting of the Acoustical Society of America, 1978.

7. "An Environmental-Acoustics Model for a Deep Moving Ocean," 95th Meeting of the Acoustical Society of America, 1978.

8. "Short-Range Sound Transmission between Moving Receivers and Sources in the Deep Ocean," 97th Meeting of the Acoustical Society of America, 1979.

9. "Phase Variations in Short-Range Transmissions Produced by Cyclonic Eddies," 97th Meetingof the Acoustical Society of America, 1979.

10. "Environmental Acoustics of Mesoscale Eddies," Cornell University, 1979.

11. "Modeling and Acoustical Effects of Mesoscale Eddies and Rings," Northwestern University, 1980.

12. "Modeling and Acoustical Effects of Mesoscale Eddies and Rings," University of Illinois, 1980.

13. "Acoustic Effects of Random Currents in an Ocean with Linear Sound Speed," 99th Meeting of the Acoustical Society of America, 1980.

14. "Deep-Ocean Sound Transmission between Moving Receivers and Sources at Intermediate Ranges," 99th Meeting of the Acoustical Society of America, 1980.

15. "Qualitative Theory of Geometrical Spreading Loss in Stratified Acoustical Media," SIAM National Meeting, 1980.

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1. REPORT NUMBER RPI Math. Rep. No. 157	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Final Report O.N.R. Contract No. N00014-76-C-0288 1 September 1975 - 15 January 1986.		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M. J. Jacobson and W. L. Siegmann		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0288
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rensselaer Polytechnic Institute Troy, New York 12180-3590		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 386-606
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Code 425 Department of the Navy Arlington, Virginia 22217		12. REPORT DATE 14 March 1986 13. NUMBER OF PAGES 27
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This is the Final Report for O.N.R. Contract No. N00014-76-C-0288. It summarizes research results and lists publications, presentations, and supported graduate students.		

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